



## Nature's limit to the wind energy extractable for human use

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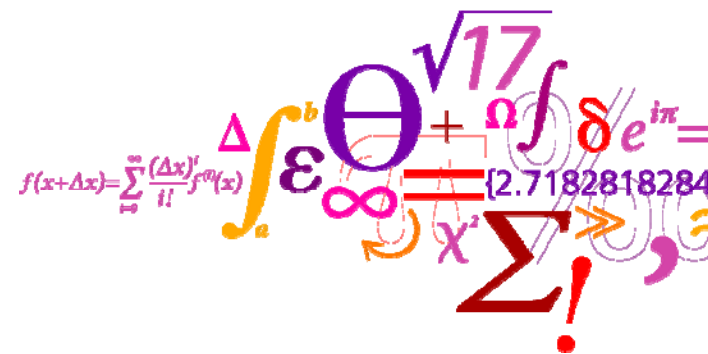
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# Nature's limit to the wind energy extractable for human use

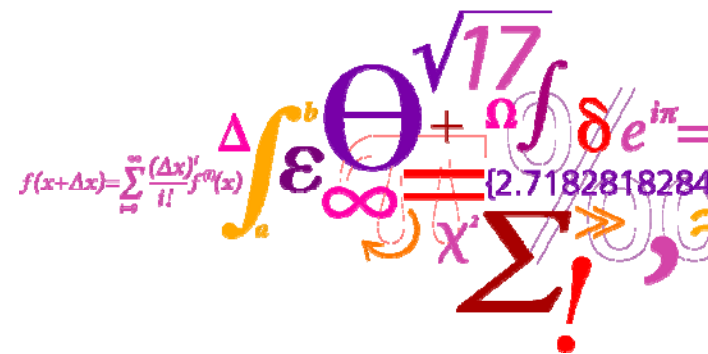
Sten T. Frandsen, Andrea N. Hahmann, Søren E. Larsen  
Risø DTU  
Aksel W. Hansen  
NBI Copenhagen University



# Climate change mitigation

## – what are the realistic options?

- Amongst the renewables, wind appears presently unchallenged, being much cheaper than the runners-up.
- Wind is known to be abundant – how abundant?
- It influences the climate marginally – how marginally?

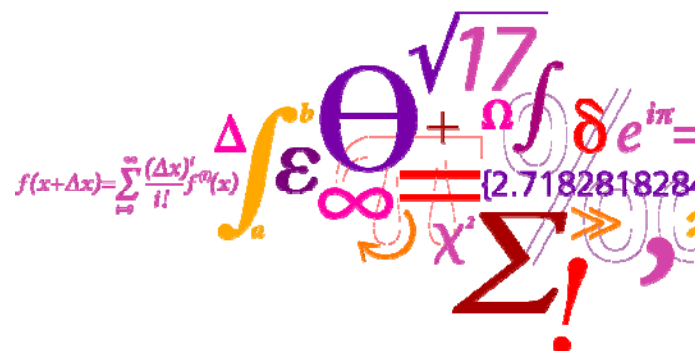


# Synopsis

- Simple extrapolation of wind power contribution to world energy.
- Some uncertainties in predicting future availability of wind power from both technology and nature.

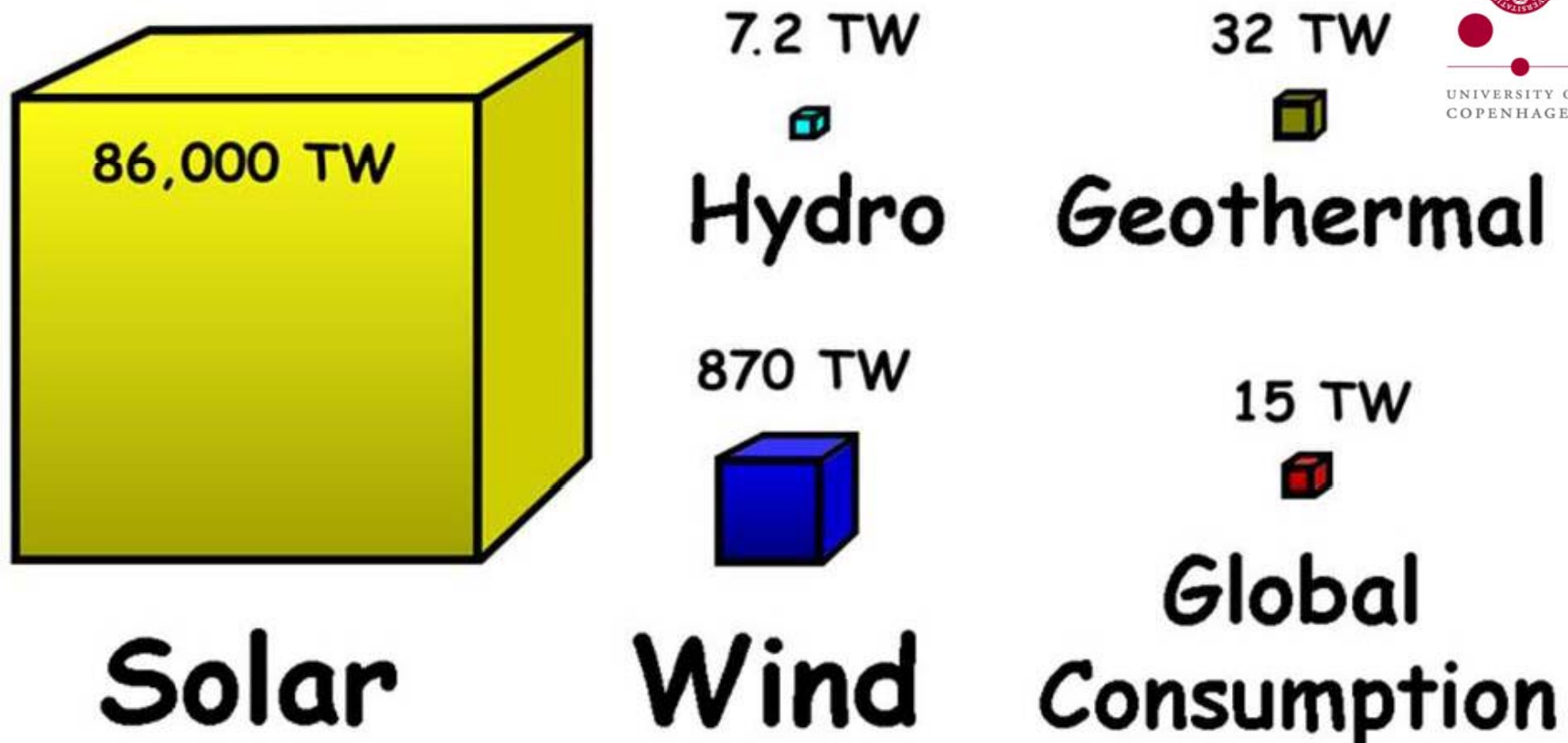
Example from wind power over the North Sea Europe, including individual turbine wakes but not wind farm shadows and regional feed-back.

- Global atmospheric motion, upper limit to available energy and regional and global feed –back from the extraction.



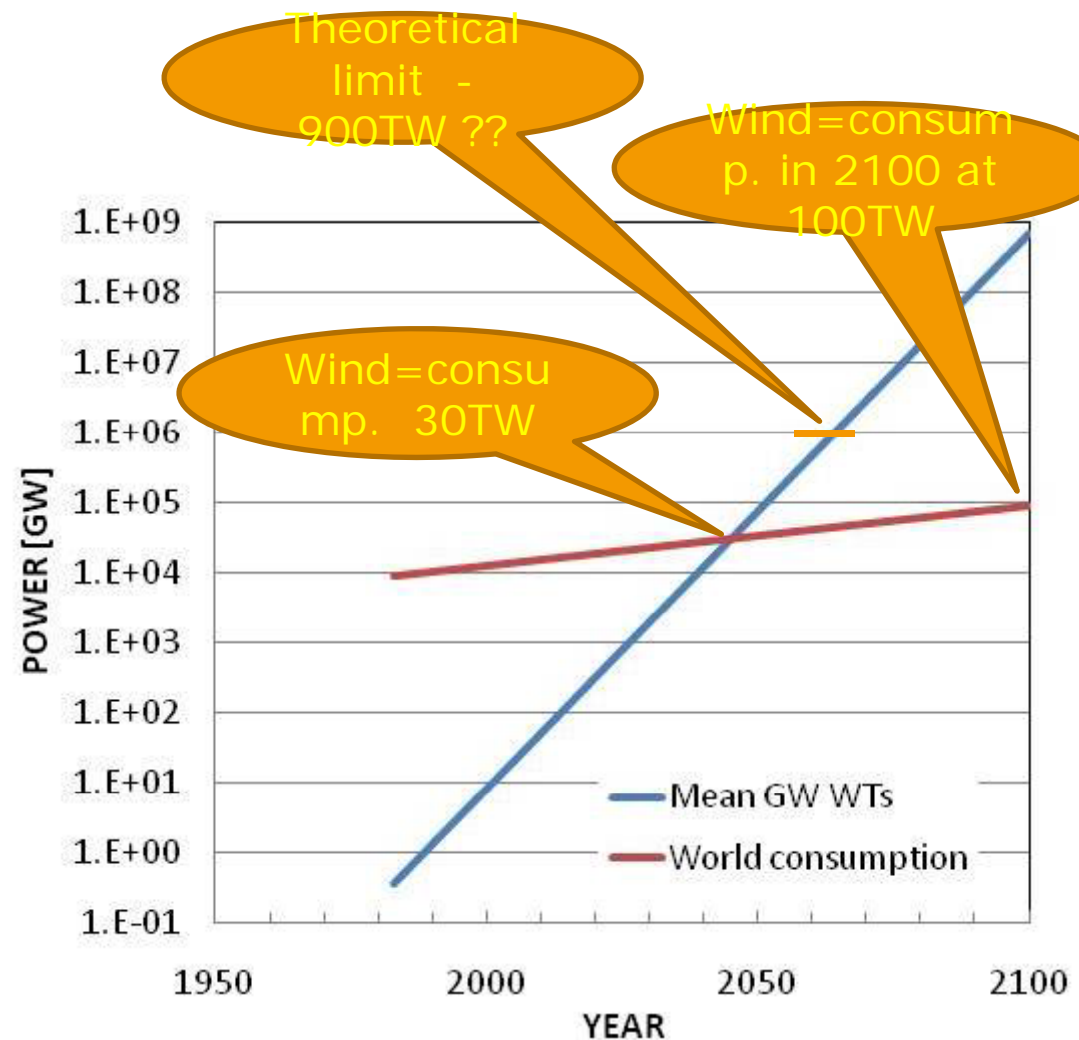
# Renewable energies

How much is there? And how much is used already now? (annual mean power)



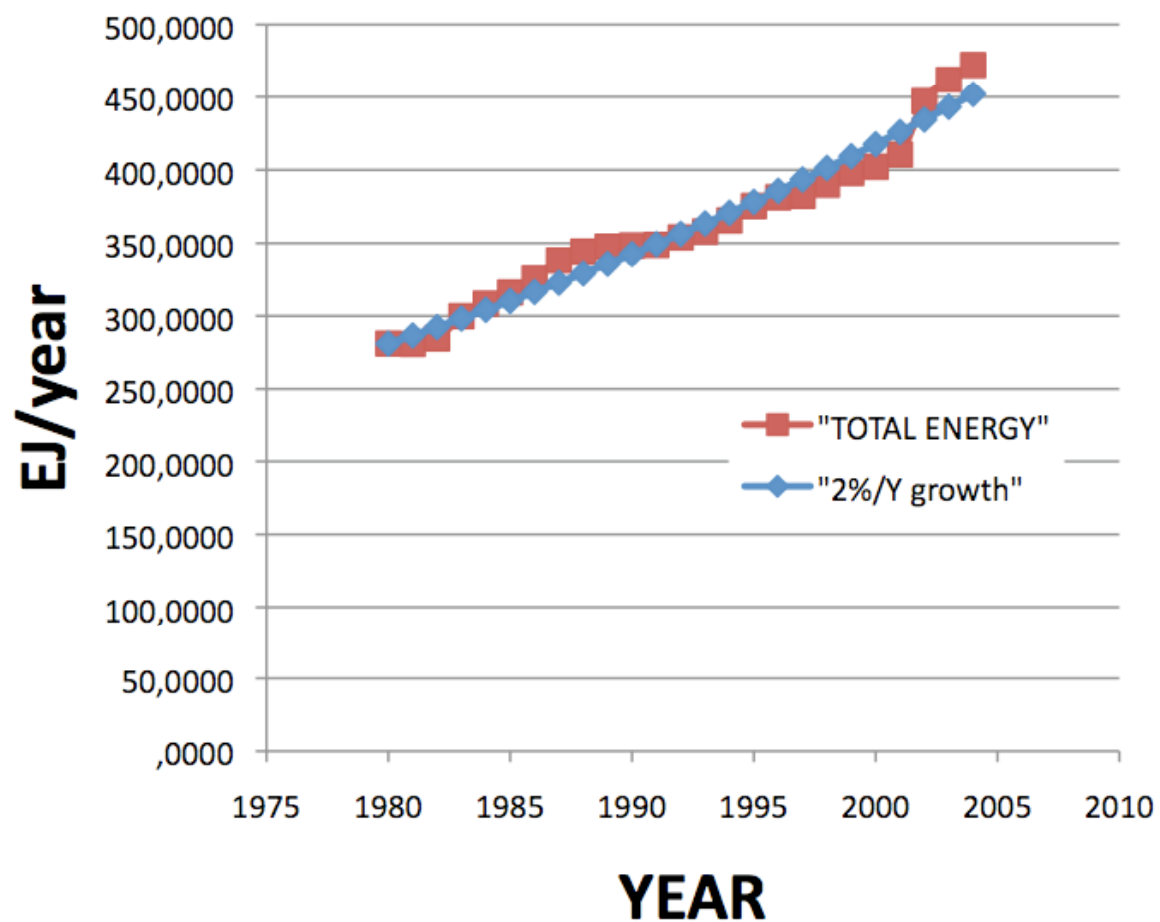
## Prognoses: consumption and wind energy

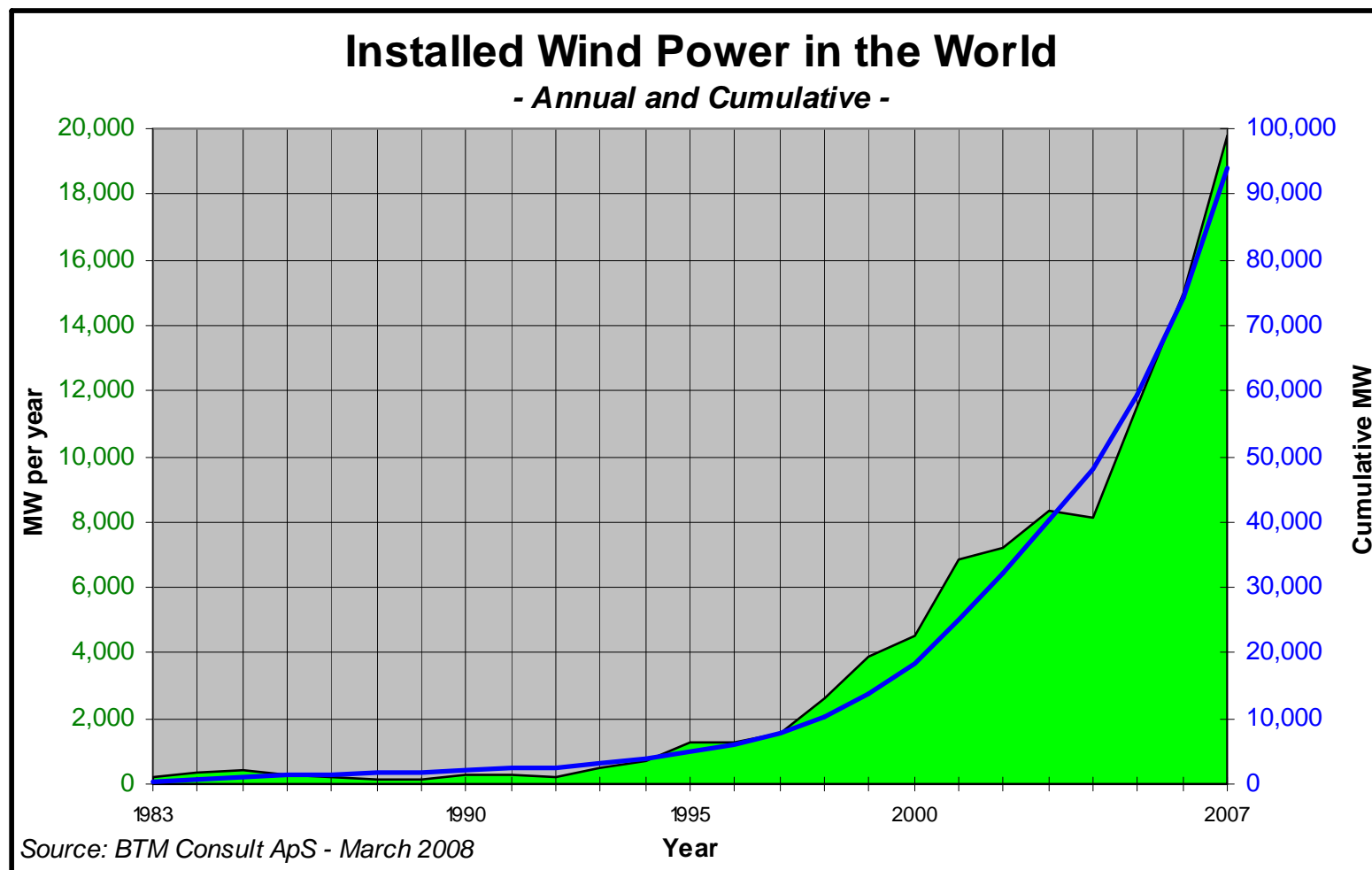
- Consumption growth rate: 2% per year
- Wind power industry growth rate: 20%
- **Wind=consumption in approx. 2050 at 30TW**



## Total energy consumption

Energy consumption is in fact growing at 2% pr year

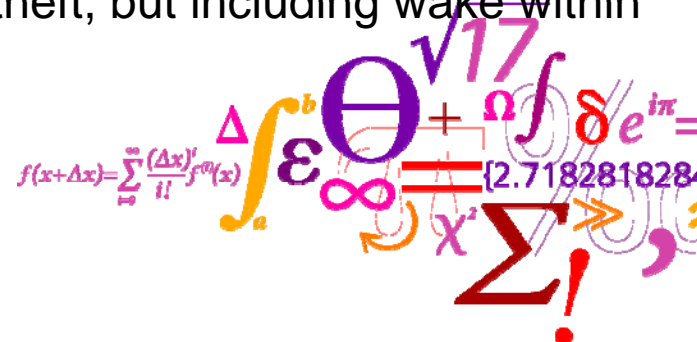






# Development of wind energy and its uncertainties.

- Characteristics of wind energy: Variability.
- Reduction of output due to wake effects
  - a) between turbines.
  - b) wind shadowing and wind theft between wind farms(?).
- Future development of wind turbines
- The North Sea as a suitable area for a large wind power contribution to Europe's Energy consumption, based on the production from the Horns Rev Wind Farm, neglecting wind theft, but including wake within the farm area.

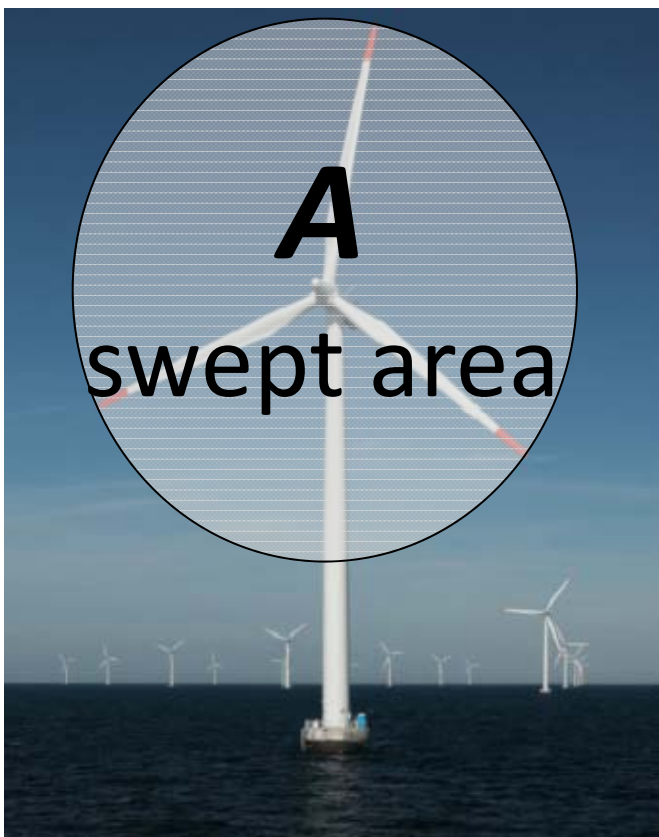


# How does the wind turbine make electricity?

$$P_{available} = \frac{1}{2} \rho U^3 A$$

wind turbine

wind



- Energy in the wind goes with  $U*U*U$ ; therefore:
- **20% more wind-  
70% more energy**
- **100% more wind-  
700% more energy!!**

# Wind turbines

..obstruct each other—  
and interact with the atmosphere

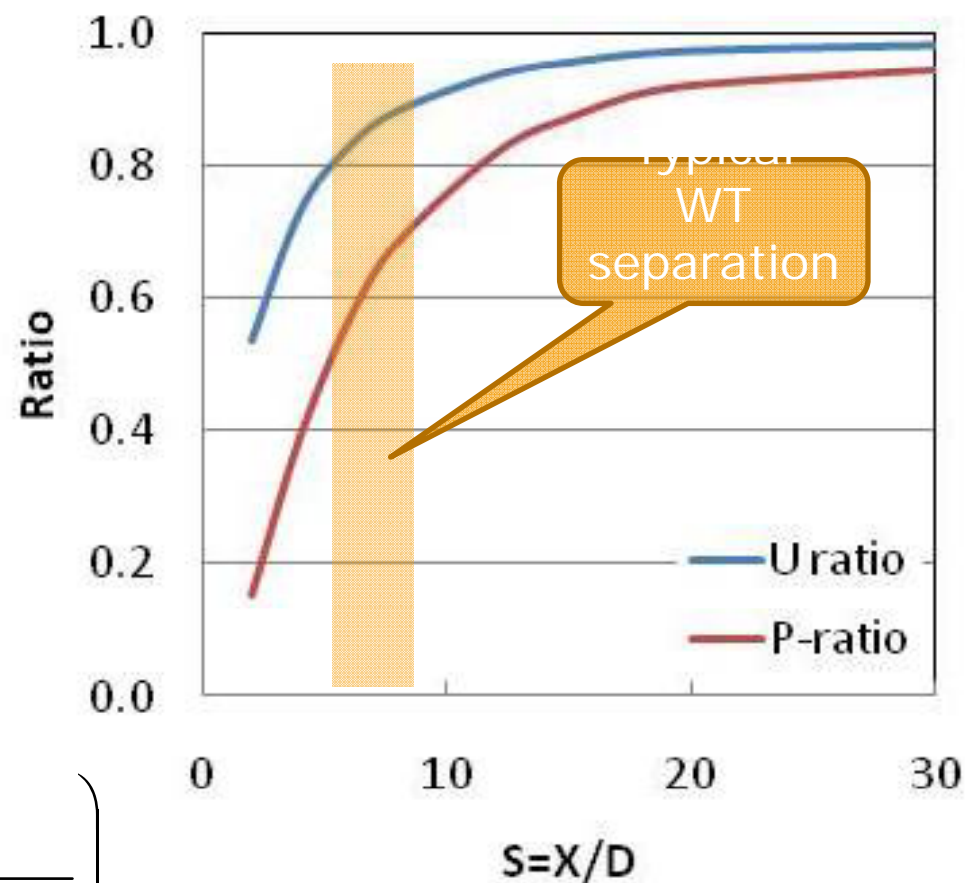


Wind farm losses relative to unobstructed wind turbines:

*roughness boundary layer model*

- Losses with present engineering tools small
- Disregarding global effects, but including feedback from wind farms to boundary layer, 40-50% losses may be seen with "standard" 7-8D separations
- Wind turbines increase the surface roughness:

Losses vs. separation

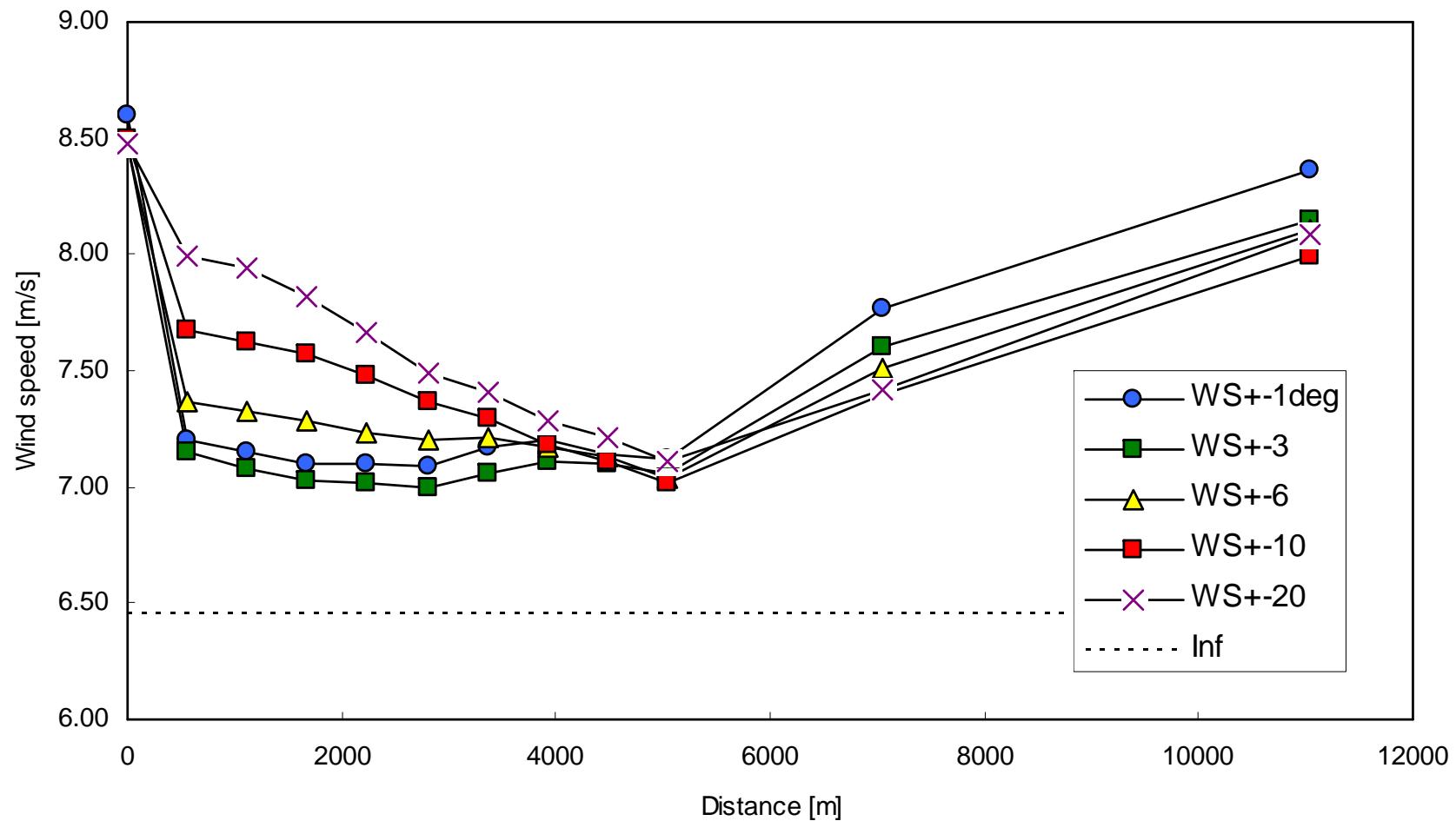


$$z_{00} = h_H \cdot \exp\left(-\frac{\kappa}{\sqrt{c_t + (\kappa / \ln(h_H / z_0))^2}}\right)$$

# Wind speed drop in wind farms - and recovery

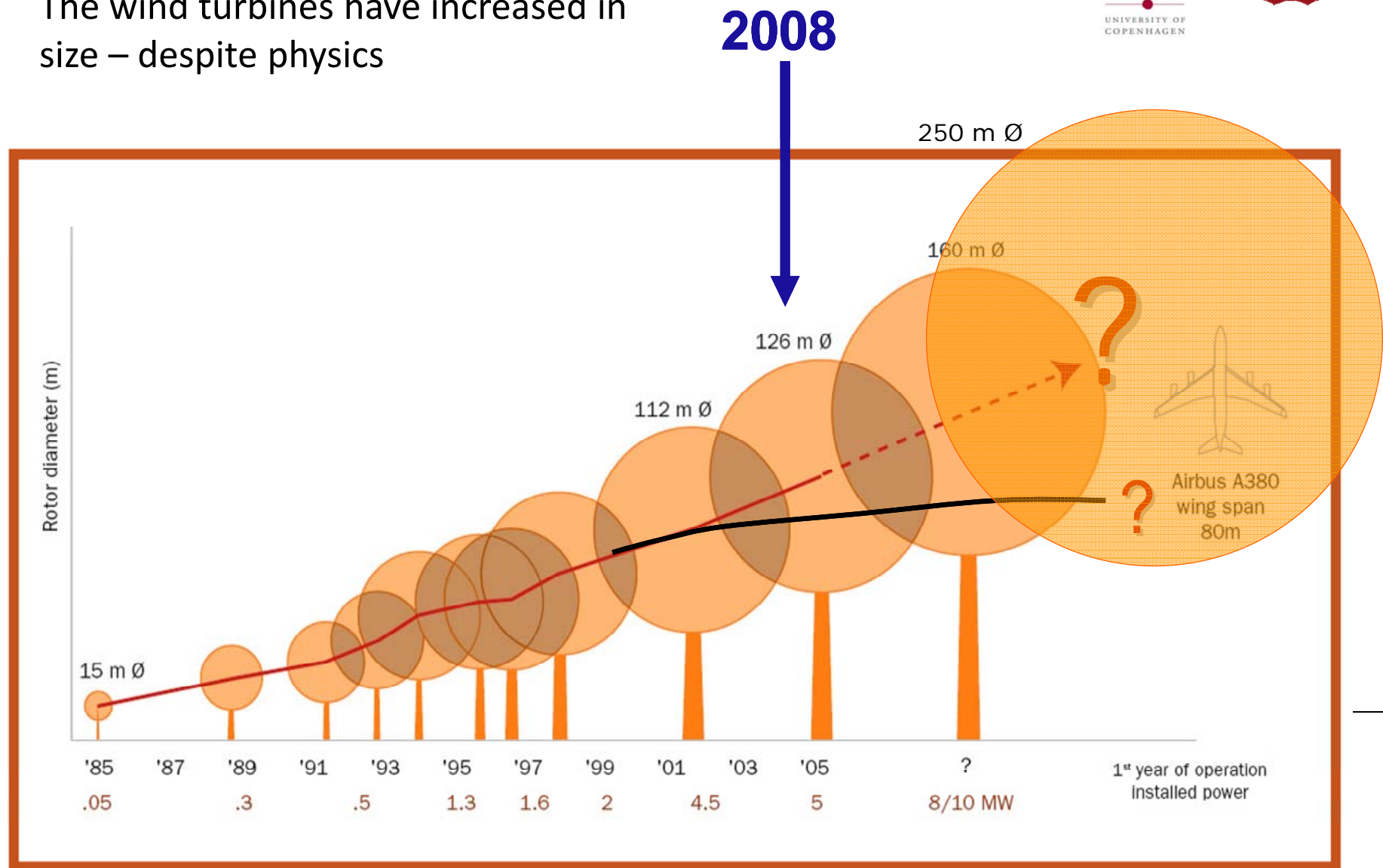


Horns Rev,  $8 < U < 9$ , wind from west



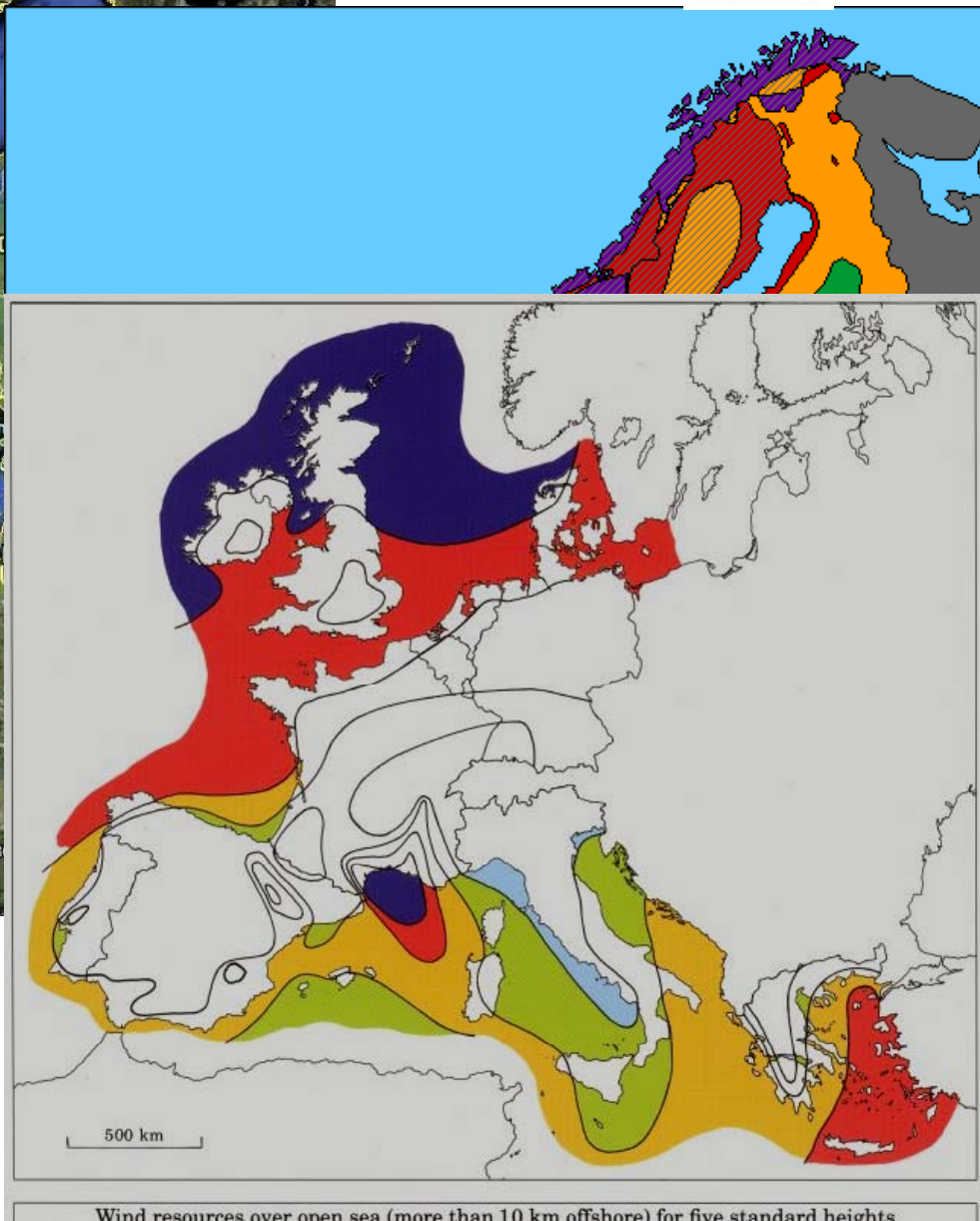
# Up-Scaling

The wind turbines have increased in size – despite physics





# The wind in the northern seas

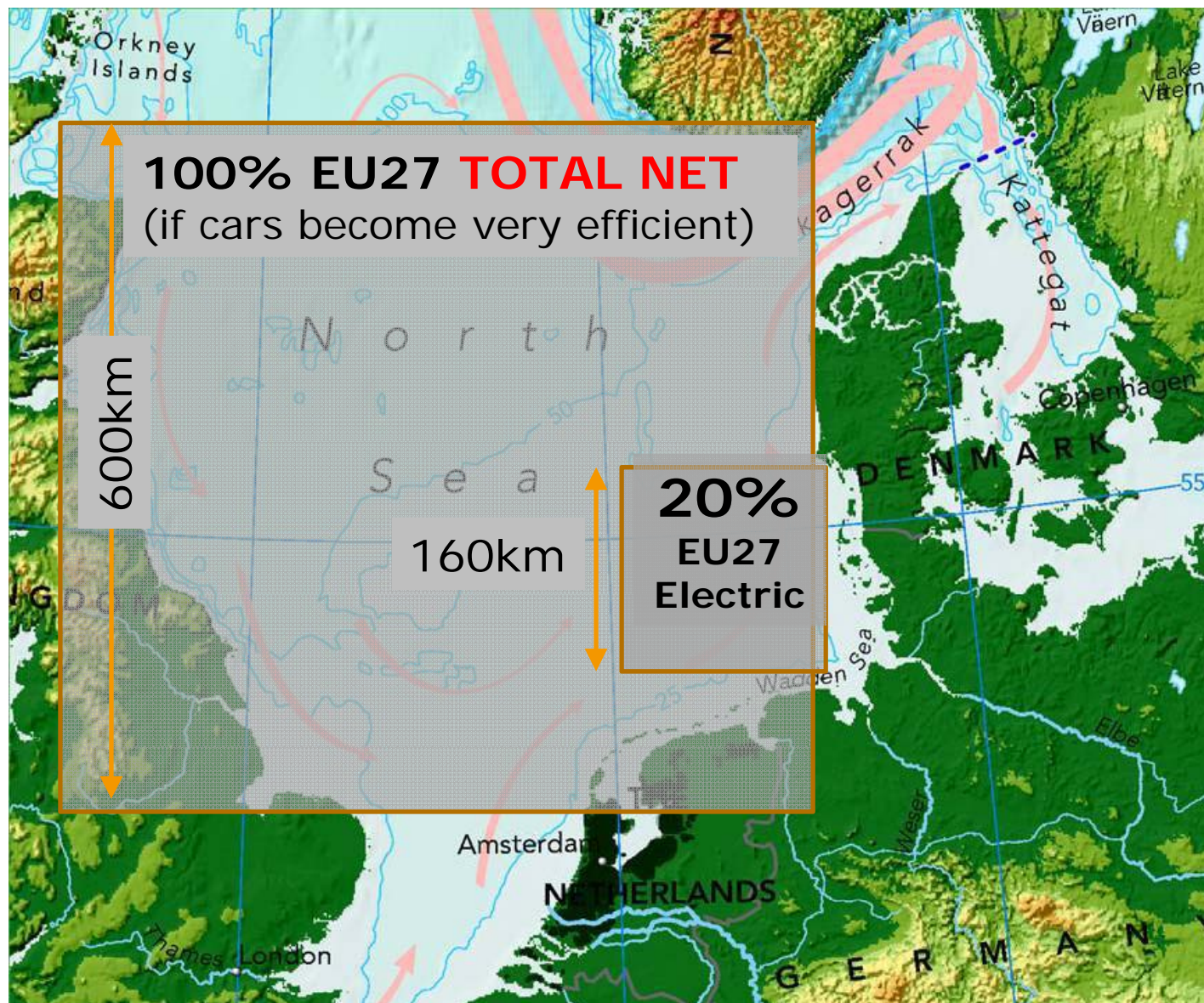


...huge wind farm areas are needed in the future and somehow wind farms affect the atmospheric flow also on the larger scale

Risø DTU, Technical University of Denmark



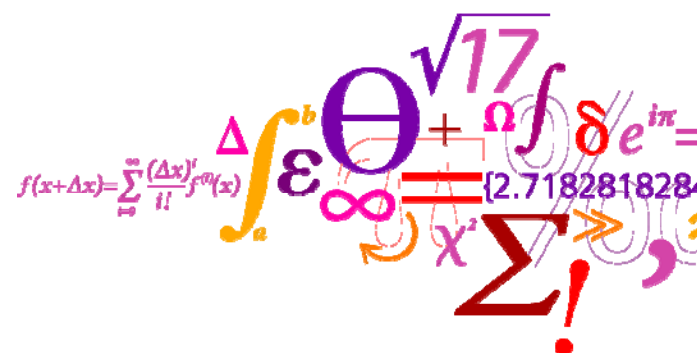
## North Sea Wind (super Horns Rev farm)





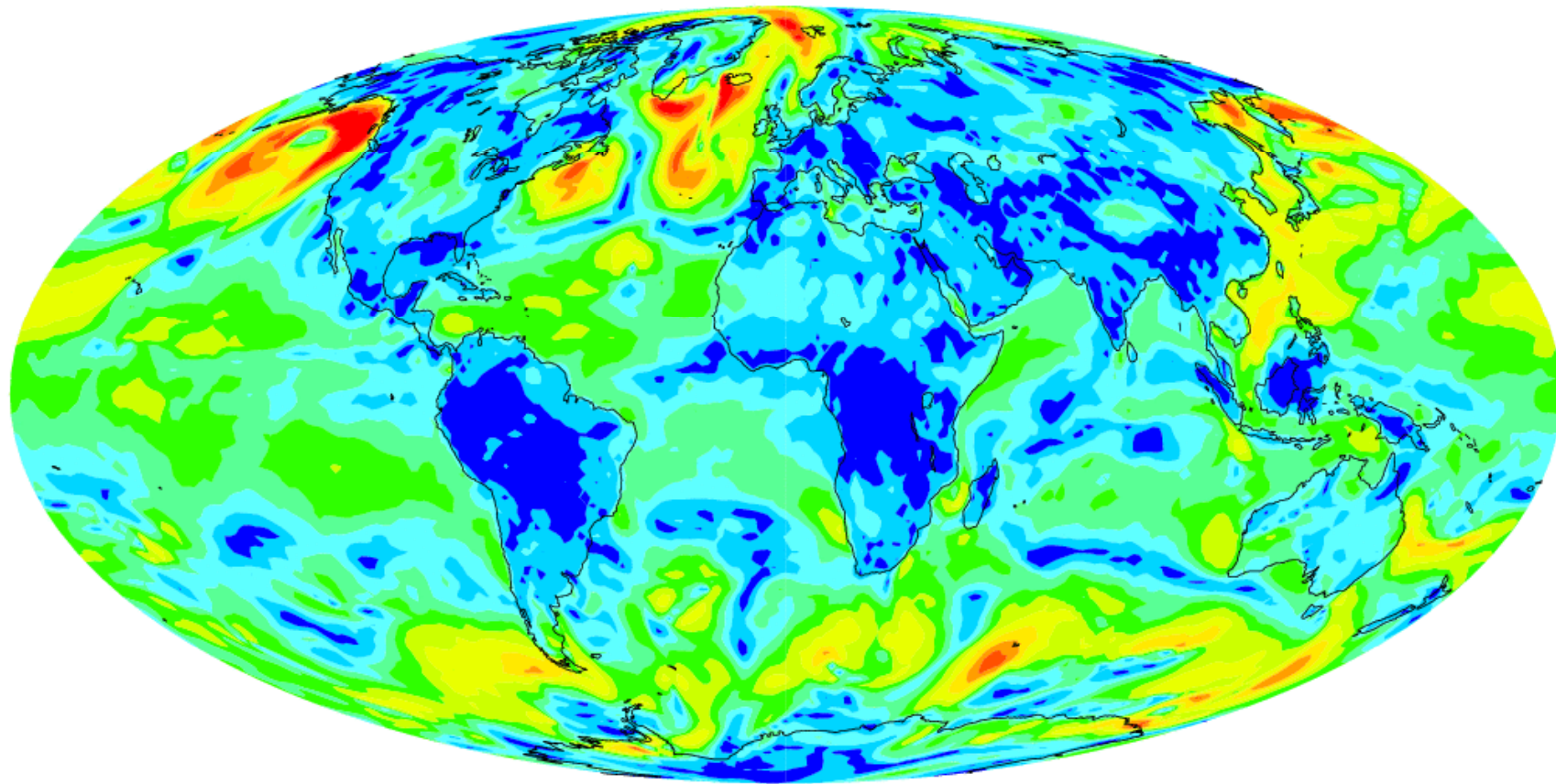
## Large scale impacts.

- Global atmospheric motion, upper limit to available energy and feed – back from the extraction.
- The energy available extraction equals the energy that is dissipated in the Atmospheric Boundary Layer due to friction between the atmosphere and the ground. In a sense wind turbines are “just” a new dissipation mechanism in addition to “natural surface friction”.



# Wind speed during January 2008

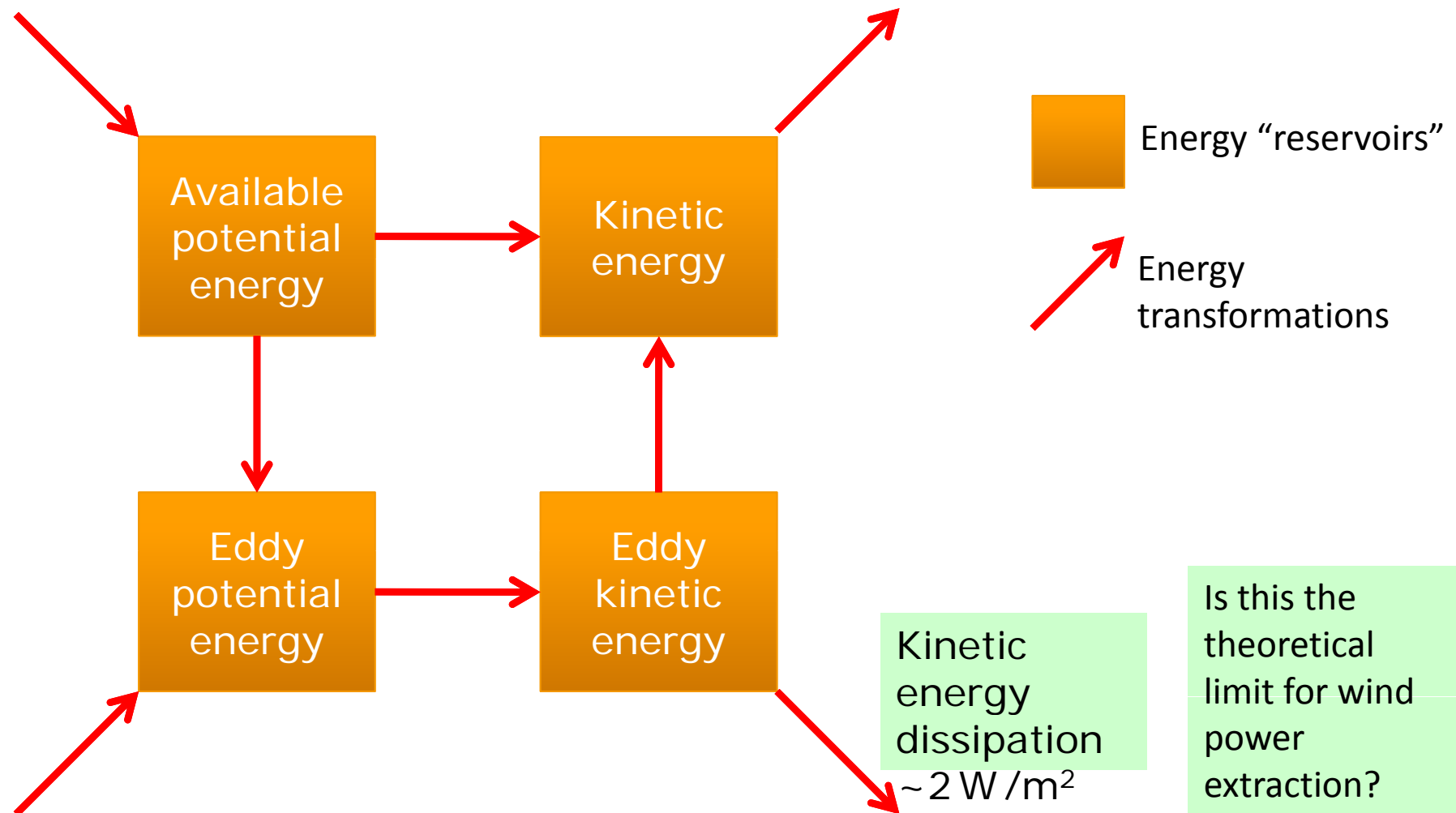
01/01/2008 (00:00)



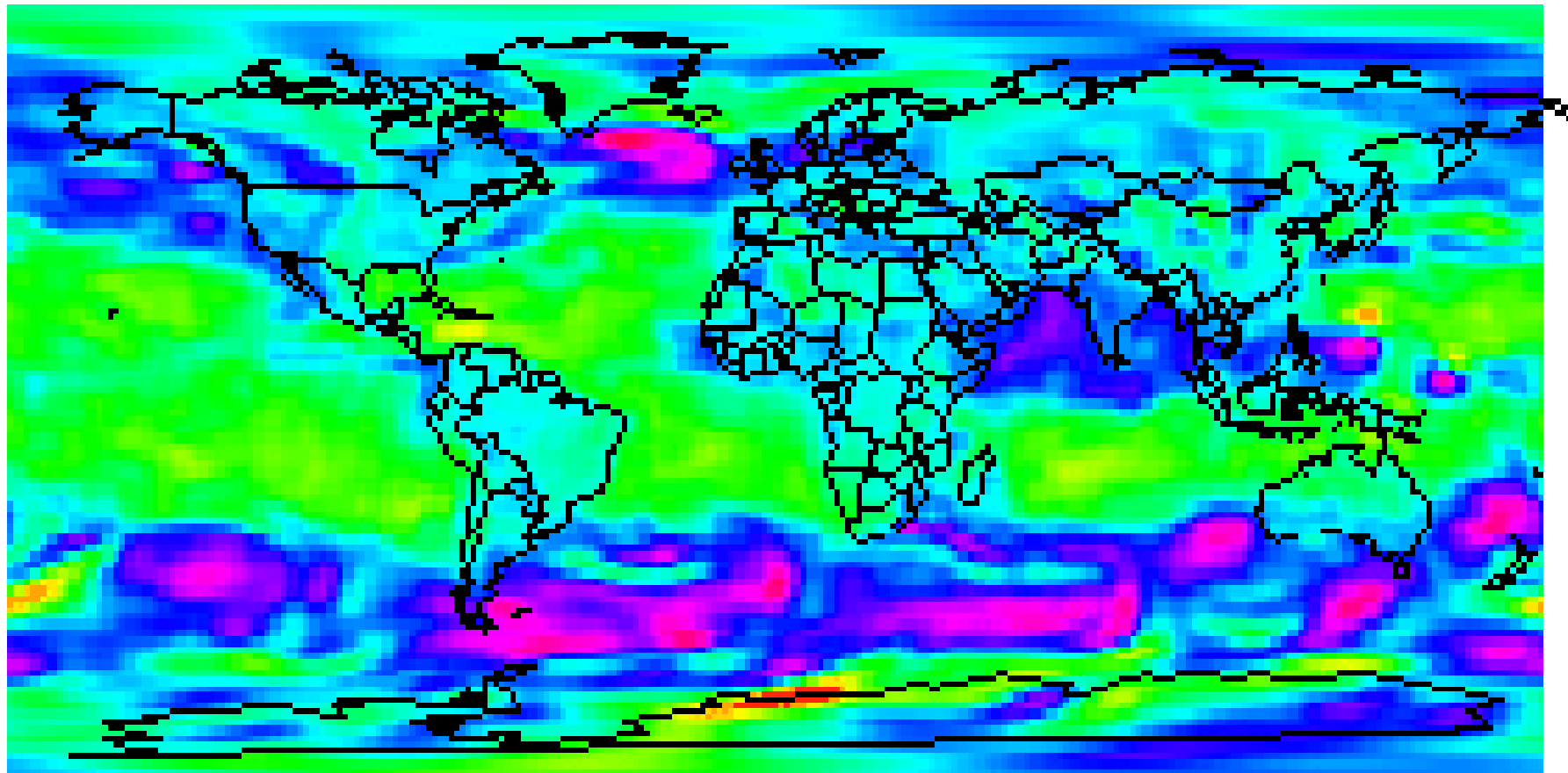
2 4 6 8 10 12 14 16 18 20

10-m AGL wind speed (m/s)

## Global energy cycle (the Lorenz Cycle)



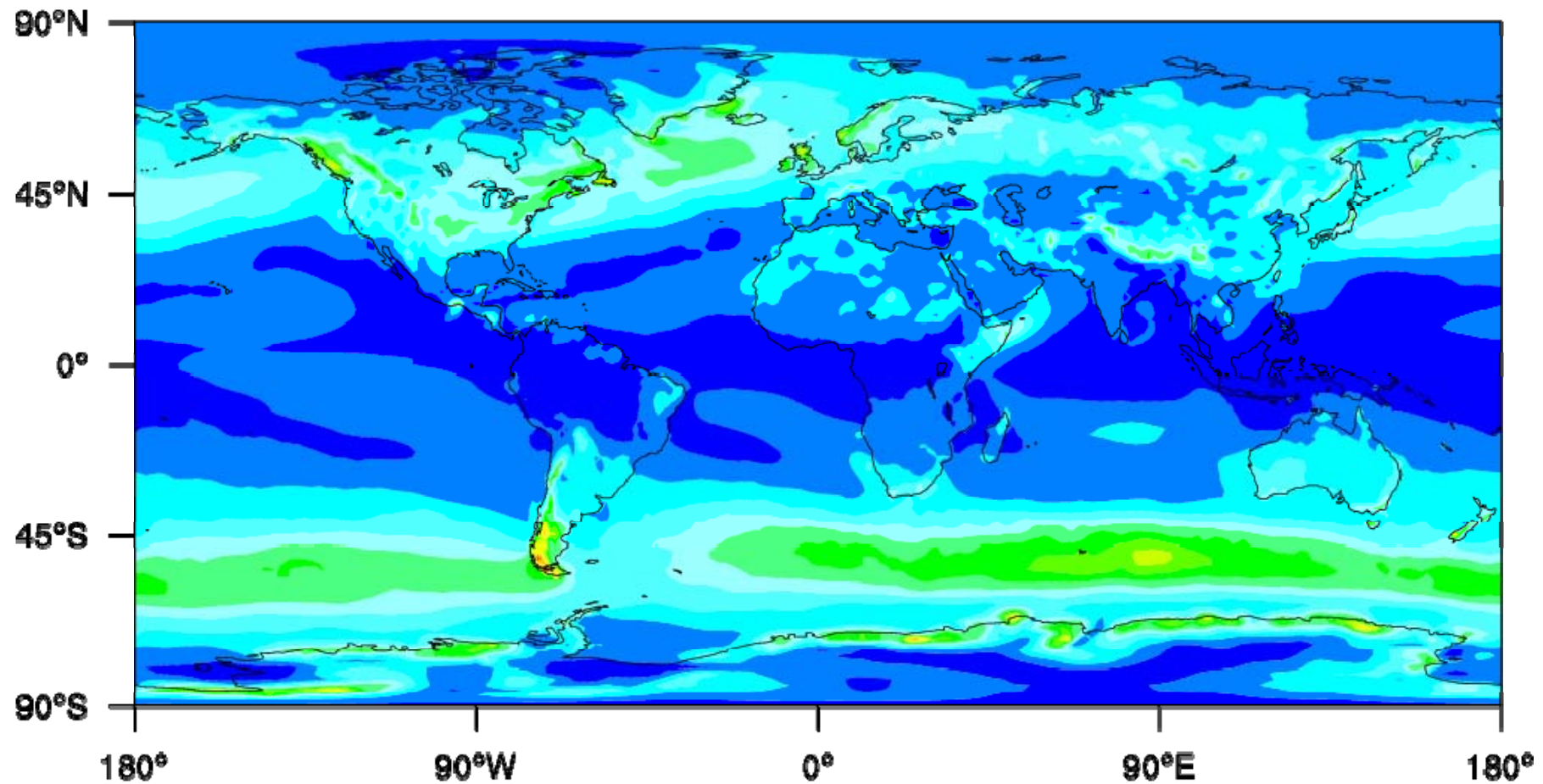
# The global wind systems



Boundary layer dissipation ( $\text{W/m}^2$ ) derived from ECMWF (European Centre for Medium Range Forecast) Reanalysis (ERA Interim,  $1.5^\circ$  resolution) for 2008

## Boundary layer dissipation (2008)

$\text{W/m}^2$



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# Weather and Climate Impacts of wind farm installations?

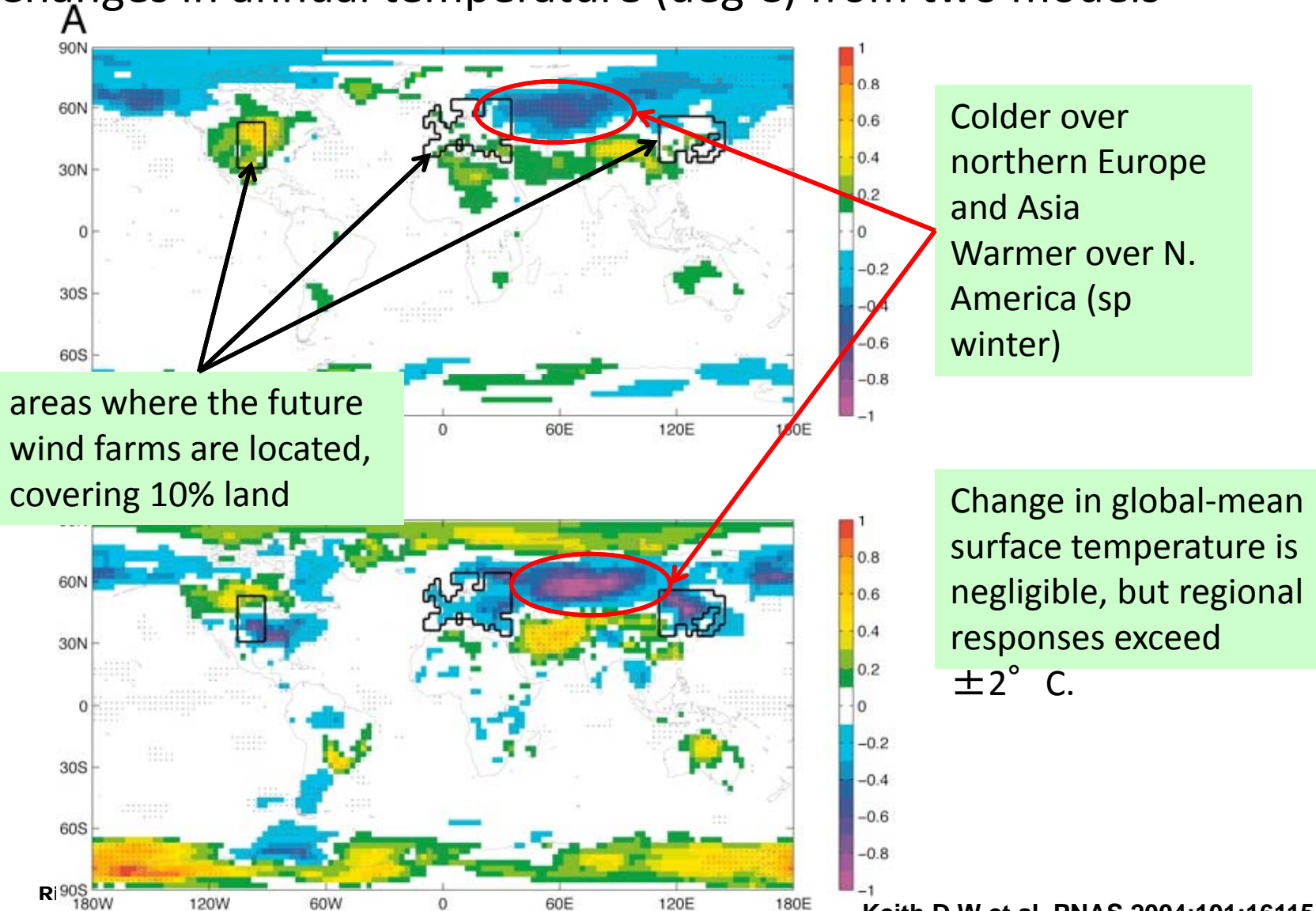


- Under present day wind-power capacity, only a very small fraction of the available kinetic energy is extracted
- If the area were to increase, what would be impacts on weather and climate?
- Past studies have shown that:
  - Local meteorology: there are considerable changes within and downstream of the wind farm (winds slow down, increased turbulence, enhanced turbulent mixing of heat and water vapor) (Baidya Roy et al. 2004).
  - Effects can be seen from satellite imagery when large wind farms are offshore (Christiansen and Hasager 2005)
  - There is a potential for significant changes to surface climate as large-scale development approaches the limit of available kinetic energy (Keith et al 2004; Kirk-Davidoff and Keith 2008)

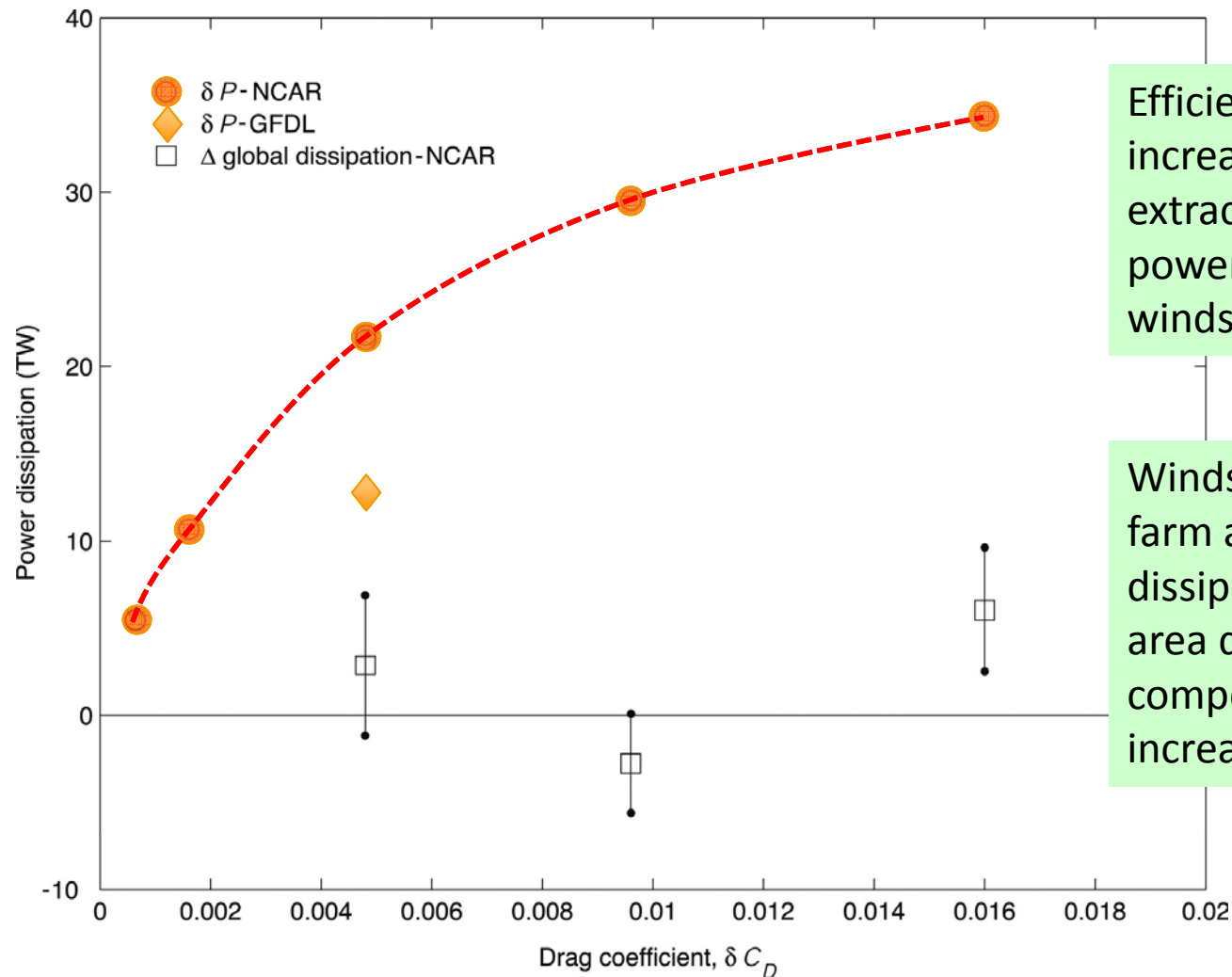


# Climate impacts from general circulation model (GCM) experiments (Keith et al. 2004)

## Changes in annual temperature (deg C) from two models



# Change of Energy dissipation versus change of drag



Efficiency by which increased surface drag extracts additional power declines because winds slow down

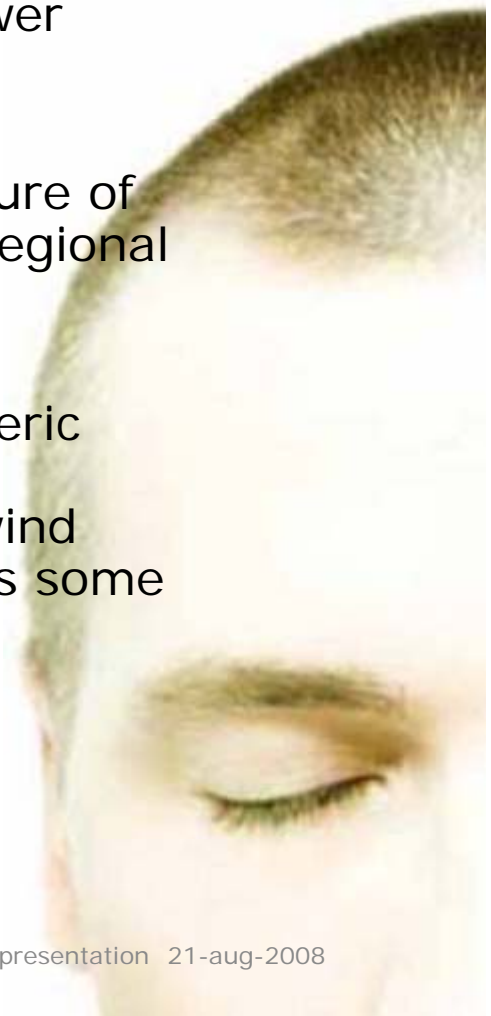
Winds outside the wind farm are slowed so that dissipation outside the area decreases to compensate for the increased dissipation

Keith D W et al. PNAS 2004;101:16115-16120



# Conclusions

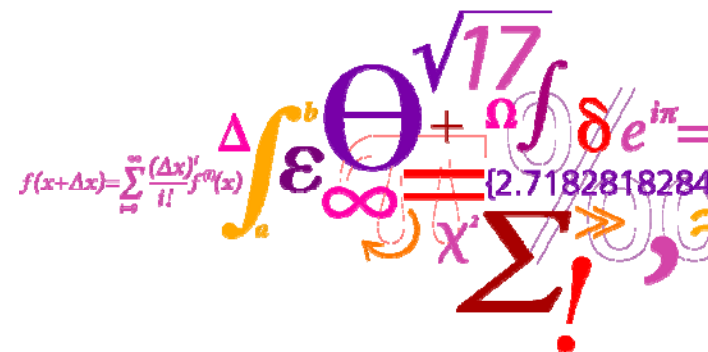
- The large-scale atmospheric dynamics (through the boundary layer dissipation) provide an upper bound on the power that can be extracted by large-scale wind power utilization.
- The extractable fraction depends on the wake structure of both individual turbines and of wind farms- and on regional scale wind climate feed-back.
- In present model experiments, the overall atmospheric structure is modified only slightly in response to the changes in surface drag, induced by installation of wind farms. Regional scale changes are noticed as well as some modification of other climate parameters.



**Thank you for your attention**



Thank you for your attention



The world needs to replace fossil fuels because:

There is only fossil fuel energy for another century with present consumption

Burning carbon leads to more insulation and thereby a heating of the climate system

Burning all known carbon will **DOUBLE/TRIPLE** the current CO<sub>2</sub> mixing ratio in the atmosphere

1300 – 1400 Gt C can be emitted, presently the atmosphere contains 750 – 800 Gt C

## ESS Meeting, May 18, 2009

Energy production rate now: 16 TW eq. to 0,03 W/m<sup>2</sup>

200 years from now we'll need: 1,5 PW eq. to 3 W/m<sup>2</sup> ?

	Present	Max rate	Remaining energy
NON-RENEWABLE			
inactive reservoir			
Fossil fuels	0,013 PW (0,400 ZJ/yr)	----	100 – 300 ZJ
Nuclear power	0,001 PW	----	???
active reservoir			
Geothermal	0,015 TW	0,025 PW	"infinite", but
Solar	0,003 TW	+ 120,000 PW	"infinite"
RENEWABLE			
(cycling or flow based)			
Biomass	0,001 PW	0,200 PW	----
Hydropower	0,001 PW	0,007 PW	----
Wind power	<0,120 TW	1,000 PW	----
Oceanic energy	zero	0,080 PW	----

**Vil vi sige noget om forskellen mellem det teoretiske max og det praktisk opnåelige max?  
Altså diskutere tallene på slide forud?**

**Vise en kurve med det stipulerede carbonfrobrug pr år, verdens krsv til energi, erstatningskildernes praktiske max-tal**

# Climate change mitigation

## what are the realistic options?



- Alternative energy sources for carbon:
  - Non renewable, but finite
    - Nuclear power      comment
  - Infinite sources
    - Solar energy      comment
    - Geothermal energy comment
  - Renewable
    - Hydropower      comment
    - Biomass      comment
    - Wind      comment
    - Ocean power      comment
- Amongst these substitutes for carbon wind appears presently unchallenged, being much cheaper **PR GW**? than the runners-up
- Wind is known to be abundant – how abundant?
- Wind energy dissipation affects the climate – how much?



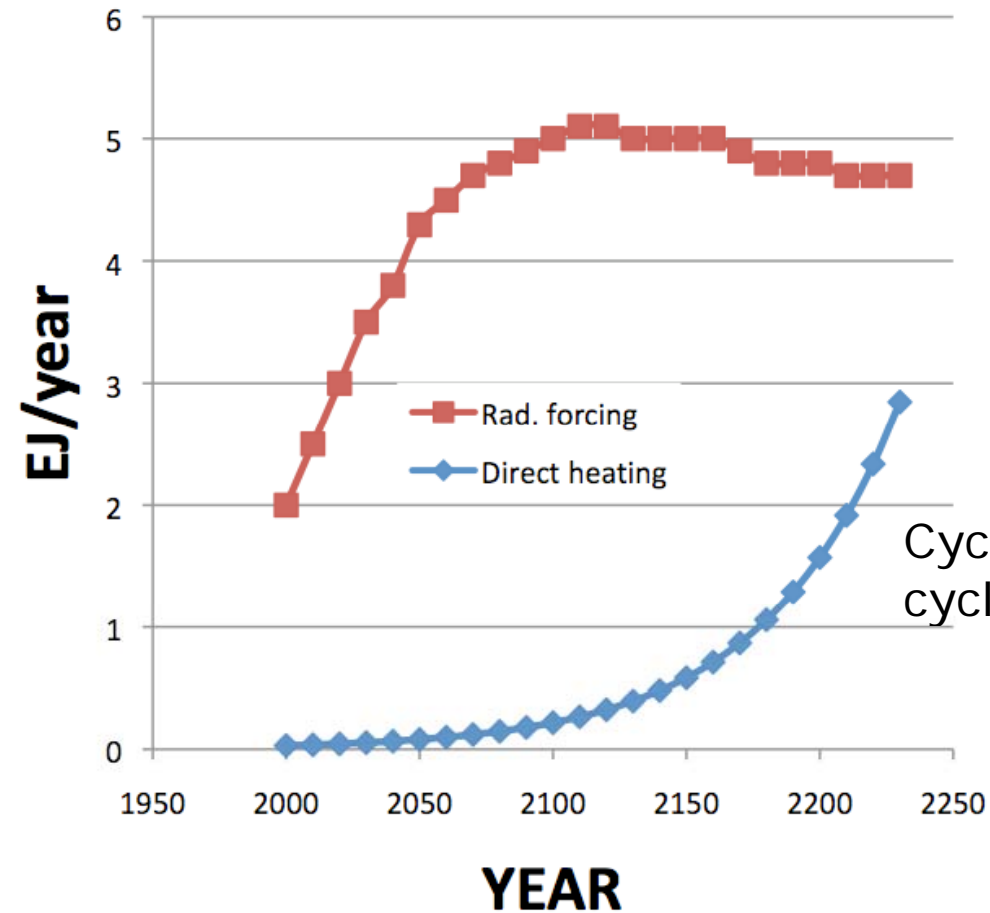
## ESS Meeting, May 18, 2009

- Answers to the two questions
  - Can we produce energy enough in the future?
    - Fossil fuel must be abandoned (greenhouse effect)
    - And in fact, there is not enough coal, gas and oil
    - Solar energy can meet the demand, but should be dealt with very carefully
- Will the climate/environment be affected adversely from 1,5 PW even with green technology?
  - Yes, probably



Greener technology versus growing demand for energy

$$\Delta T_s = RF/\lambda$$



# Offshore wind farms replacement scenarios



SCENARIO	Mean Power	Installed Wind Power	Area Needed	Square side	Investment costs
<b>Denmark 40% of EL</b>	3.2 GW	3.6 GW	530 km <sup>2</sup>	23 km	3 billion €
<b>EU27 20% of EL</b>	80 GW	160 GW	27000 km <sup>2</sup>	160 km	320 billion €
<b>EU27 40% of EL</b>	160 GW	360 GW	53000 km <sup>2</sup>	230 km	640 billion €
<b>EU27 50% of total</b>	1300 GW	2600 GW	430000 km <sup>2</sup>	660 km	2600 billion €
<b>50% of Peak North Sea Oil (1998)</b>	225 GW	450 GW	70000 km <sup>2</sup>	270 km	440 billion €

Risø DTU


SF 23062009

## World Market Growth rates 2002-2007

Year:	Installed MW	Increase %	Cumulative MW	Increase %
2002	7,227		32,037	
2003	8,344	15%	40,301	26%
2004	8,154	-2%	47,912	19%
2005	11,542	42%	59,399	24%
2006	15,016	30%	74,306	25%
2007	19,791	32%	94,005	27%
<b>Average growth - 5 years</b>		<b>22.3%</b>		<b>24.0%</b>

Source: BTM Consult ApS - March 2008

# Installed capacity in 2006 and 2007 (Global)

	Installed MW 2006	Accu. MW 2006	Installed MW 2007	Accu. MW 2007	% of installed MW 2007
Total Americas	3,515	13,577	5,815	19,391	29.4%
Total Europe	7,682	48,627	8,285	56,824	41.9%
Total South & East Asia	3,220	8,963	5,010	13,973	25.3%
Total OECD-Pacific	491	2,628	597	3,220	3.0%
Total Africa	109	386	83	469	0.4%
Total other continents and areas:	0	124	3.0	127	0.0%
Annual MW installed capacity	15,016		19,791		
Cumulative MW installed in the world		74,306		94,005	

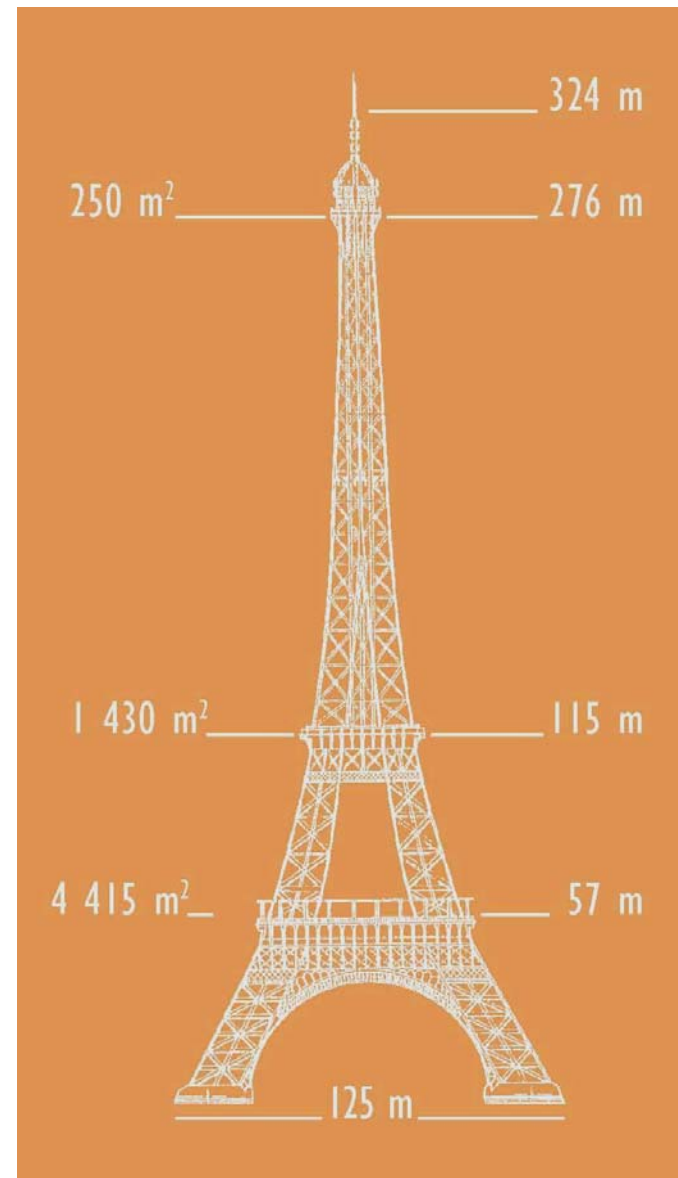
Source: BTM Consult ApS - March 2008

# The future's 20MW wind turbine and Eiffel tower



36 Risø DTU

$\approx 300m$



Siemens Erlangen 06112008

# Giant wind turbines – and houses



Risø DTU, Technical University of Denmark



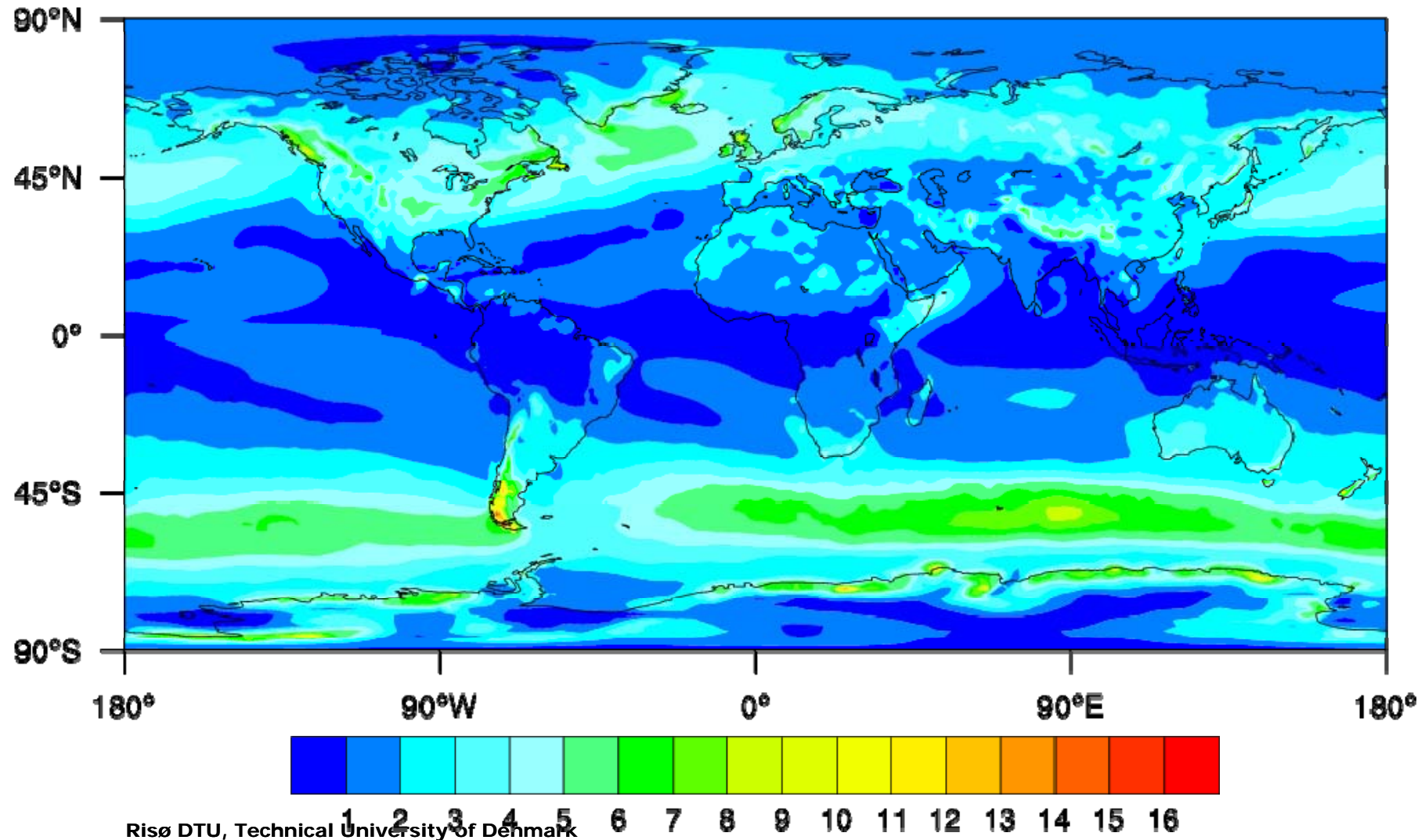
Pearl River Tower, Guangzhou

300m

Boundary layer dissipation ( $\text{W/m}^2$ ) derived from ECMWF (European Centre for Medium Range Forecast) Reanalysis (ERA Interim,  $1.5^\circ$  resolution) for 2008

## Boundary layer dissipation (2008)

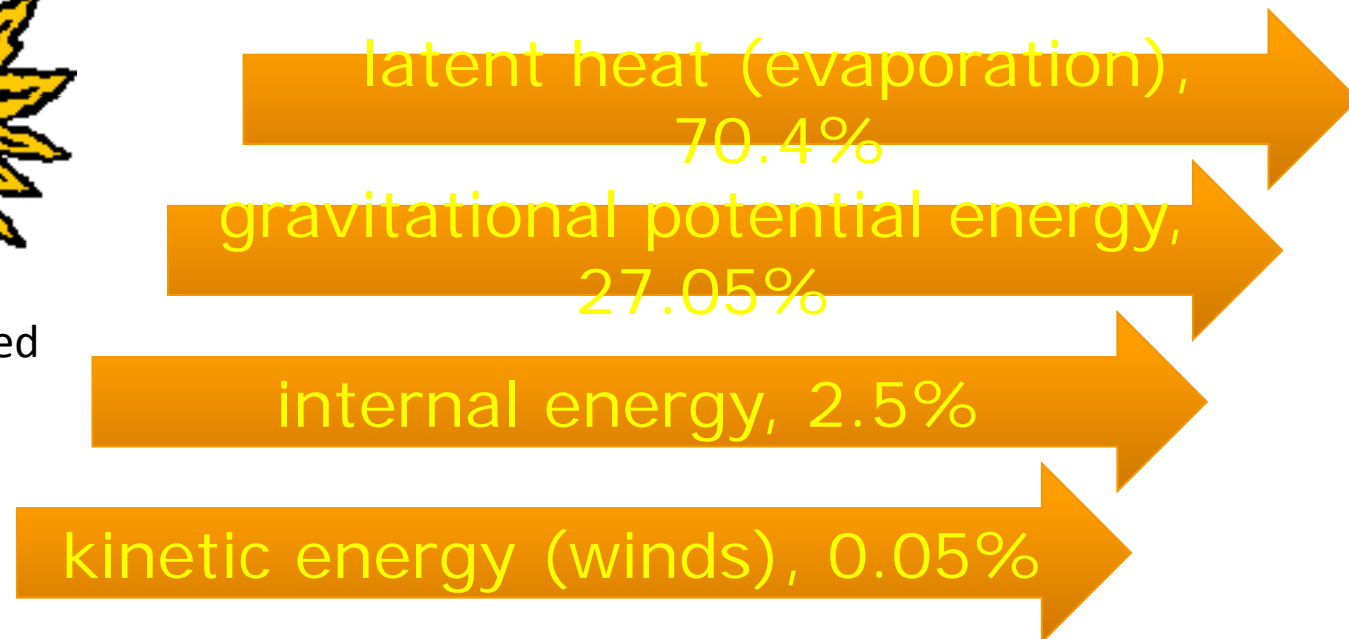
$\text{W/m}^2$



# Global Energetics



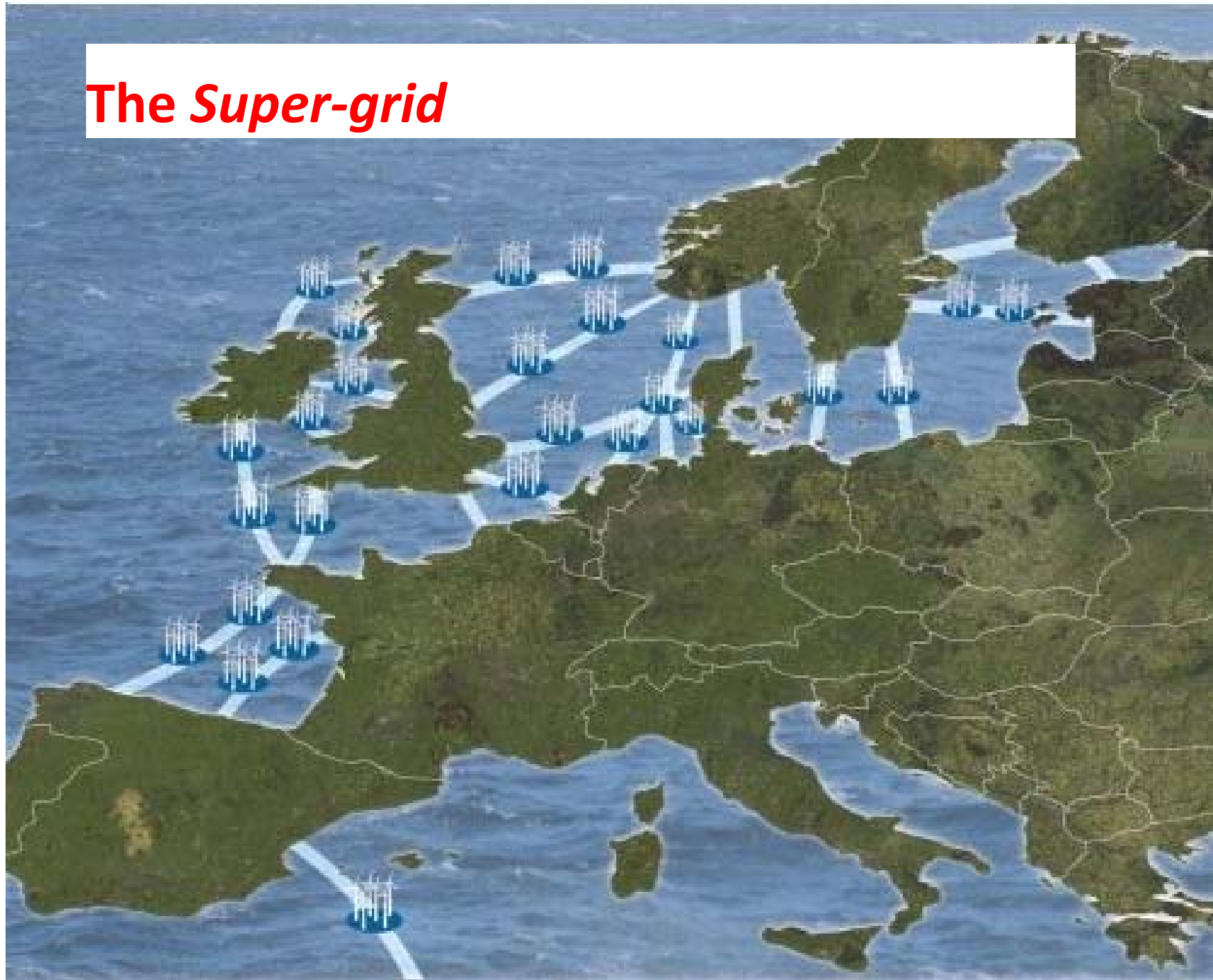
Energy absorbed  
by the Earth



Only a small fraction of this  
is available to be extracted  
by wind farm installations



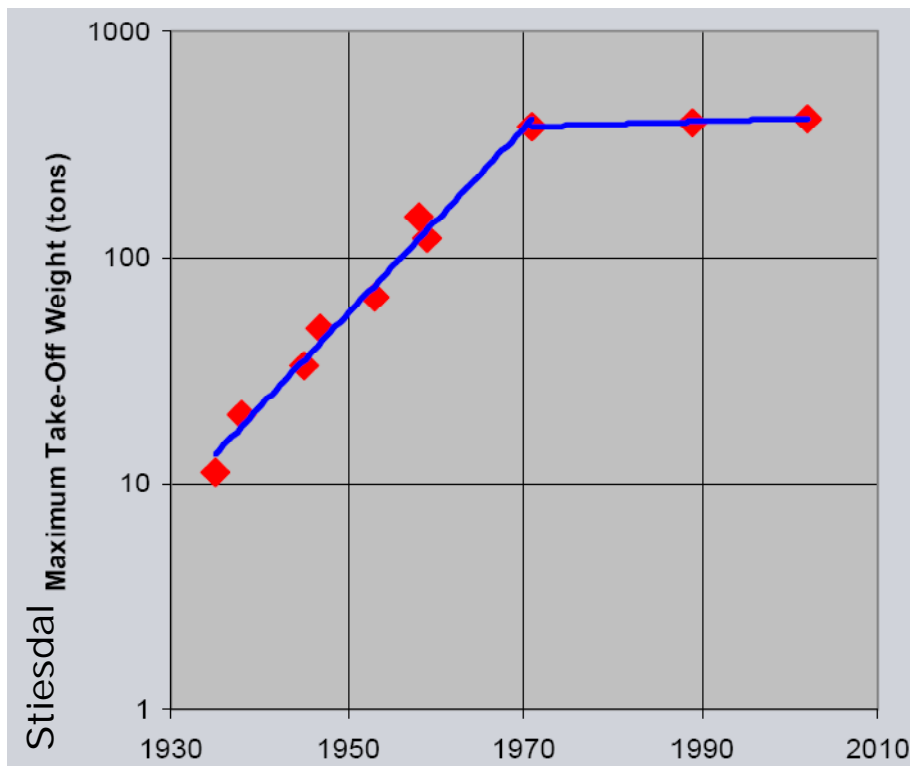
# *The Super-grid*



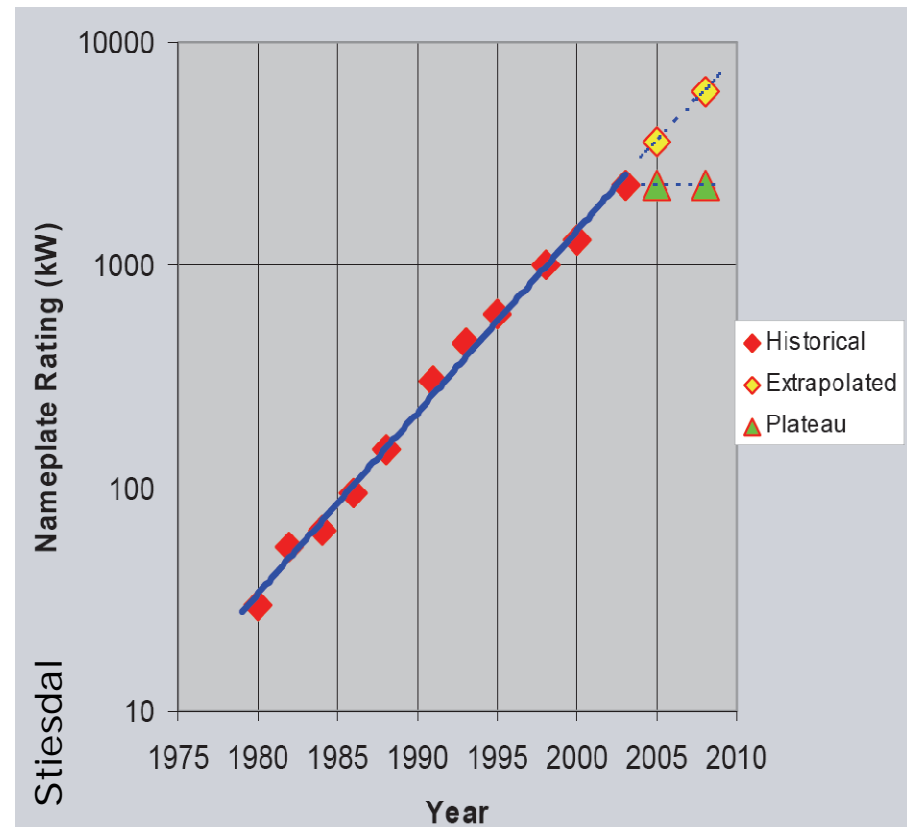
# Large planes and wind turbines over time...

....shearing a problem with the bumblebee?

## Airplanes



## Wind turbines



# The wind pits of Europe – The North Sea

- Excellent wind resources  
10-11 m/s average
- Manageable water depths
- Large population densities around it
- Vast in size

